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Tiandong Guo
jihwan@pusan.ac.kr

Jin Yong Jang

Sangchul Do

Ji Hwan Jeong

Bongjun Choi

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Guo Tiandong[1], Jin Yong Jang[1], Sangchul Do[1], Ji Hwan Jeong[1]*, Bongjun Choi[2]

[1] School of Mechanical Engineering, Pusan National University, Busan, 609-735, Korea
(+82-51-510-3050, +82-51-512-5236, jihwan@pusan.ac.kr)

[2] Department of Refrigeration Air-conditioning and Energy System, Pusan National University, Busan, 609-735, Korea
(+82-51-510-3050, +82-51-512-5236)

* Corresponding Author

ABSTRACT

In the present work, phenomena associated with counter current flow limitation (CCFL) were experimentally investigated using small diameter tubes in order to suggest criterion for which the oil return is secured. The test section is made of Pyrex glass tube to allow visual observation. The inner diameter of the test tube is 7mm and the height is 1m. The inclination of test tubes varied from vertical to crank type with various horizontal lengths. Water-air flow and lubricant oil-air flow were examined through a series of experiment at various liquid flow rates. In this experimental study, flow reversal and flooding phenomena were visually observed and two-phase flow rate were measured.

Flow reversal point represents the air flow rate when the liquid film begins to flow downwards in the tube below the liquid inlet location. Whole supplied liquid flows upward when the gas flow rate is larger than this value. So the flow reversal point can be interpreted as oil return criterion and the flow reversal points were measured using various shape of test section in a wide range of liquid flow rate. The gas velocities for the flow reversal point appeared to be similar over a certain range of liquid flow rate. Flooding point was defined as the air flow rate when liquid starts to flow above the liquid inlet part. The air flow rate needed to cause flooding is inversely proportional to the liquid flow rate. Both flow reversal and flooding velocity also depend on the inclination angle, horizontal length and liquid property.

1. INTRODUCTION

These days, in some refrigerators which called top-mount refrigerator, compressor is located at the top for enlarge cabinet space or better appearance design. During normal operation of a vapor compression refrigeration system, some amount of compressor-lubricating oil flows through condenser, expansion device, evaporator, and returns to compressor. When the compressor is located above the evaporator, some of oil may not return to compressor due to gravity but accumulate at some locations. Under this circumstance, the compressor do not reserve sufficient oil inventory and it would break down. In this regard, securing oil return to the compressor is crucial to a reliable operation of refrigerators which have compressors on top of them. This criterion is associated with flow reversal and Counter Current Flow Limitation (CCFL) phenomena.

For a two-phase counter flow, CCFL or flooding is defined as the maximum flow rate at which one phase start to be carried over by another flow to be a co-current flow. CCFL is one of the most important phenomena in nuclear power plant safety and other engineering applications such as reflux condensers, wetted wall columns etc.

A lot of work has been carried out on flooding in tubes with diameter larger than of 25mm which is much larger than the tube diameter of suction pipe. And most of previously studies investigated CCFL phenomena using water and air as working fluid. For normal vapor compression refrigeration system, the inner diameter of suction line is less than 10mm and has various shapes. So far, there is no a satisfactory correlation can cover all types of tube geometry and fluid properties. Mouza *et al*. (2000) observed the onset of flooding with liquid injection at upper location by conducting experiments in the counter-current flow of air and water using vertical and inclined tube with 7mm i.d. They investigated the phenomena and correlated their data using Wallis type equation and concluded that the angle of inclination plays a dominant role in flooding in small tube. However, it is not known whether that also is valid for the tube with more complex shape and lower injection of liquid. In the present work, phenomena associated with CCFL were experimentally investigated using small diameter tubes in order to suggest criterion for which the oil return is secured. The test section is made of Pyrex glass tube to allow visual observation.

The onset of CCFL is caused by the interaction between gas and fluid which flow in opposite direction in tubes. If a circular flow path is in vertical installation, the flow pattern would be an annular flow at a low gas flow rate. As the rate of upward flow of gas is increased the liquid film becomes progressively more disturbed. When the gas flow rate reaches a critical value, some of liquid is propelled by the gas flow above the liquid inlet. This is onset of CCFL or Flooding. If gas flow continues increasing, more and more liquid is pulled upwards by the gas until none of liquid penetrate blow the liquid inlet. This phenomenon is called zero penetration. If the gas flow rate is reduced progressively the liquid film begins to flow downwards at some gas flow rate. This phenomenon is called flow reversal. In this experimental study, flooding and flow reversal phenomena using water and oil as liquid phases were visually observed and two-phase flow rate were measured.

CCFL phenomenon has been analyzed by many models including empirical correlations. The most widely used correlation for CCFL in vertical tubes is as following (Wallis, 1961):

$$j_g^{*1/2} + m \cdot j_f^{*1/2} = C \tag{1}$$

Where

$$j_g^* = j_g \left(\frac{\rho_g}{g d_i (\rho_f - \rho_g)} \right)^{1/2} \tag{2}$$

$$j_f^* = j_f \left(\frac{\rho_f}{g d_i (\rho_f - \rho_g)} \right)^{1/2} \tag{3}$$

$j_g(=\alpha_g V_g)$ and $j_f(=\alpha_f V_f)$ denote the gas superficial velocity and liquid superficial velocity, respectively. g, d_i and ρ is gravitational acceleration, tube inner diameter and phase density.

Before gas flow rate induce to flow reversal point, no liquid penetrate below liquid inlet, $j_f=0$, thus

$$j_g^{*1/2} = C \tag{4}$$

$$j_g = C^2 \left(\frac{g d_i (\rho_f - \rho_g)}{\rho_g} \right)^{1/2} \tag{5}$$

The objective of this work is to perform experiments to observe CCFL phenomena in small diameter tubes and develop constant *C* in order to predict critical gas velocity for oil return design.

2. Experiments

2.1 Test Apparatus

Figure 1 is a schematic of test apparatus for performing CCFL experiments in a small diameter section tube. An upper transparent plenum maintained and cycle the liquid ejected by gas. Air provided by air compressor enters the test section through a 10cm long inlet port (Figure 2) which was made to a smooth bell-shape entry in order to eliminate the interference of entry air. A pressure regulator which is used to eliminate the fluctuation of gas flow is fitted in air line. Liquid flows into tube uniformly through a porous media section in the two phase mixer (Figure 3) located the bottom of test section. The mixer is a transparent square housing with a 10cm width a 10cm height. The feed flow rates of air and liquid are measured using rotameters. The liquid and air flow rates are controlled and adjusted by gear pump with microprocessor control and a needle valve respectively.

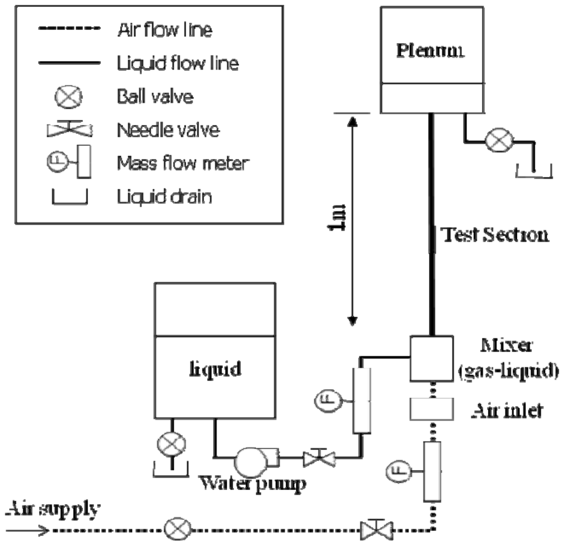


Figure 1: Schematics of Experimental apparatus

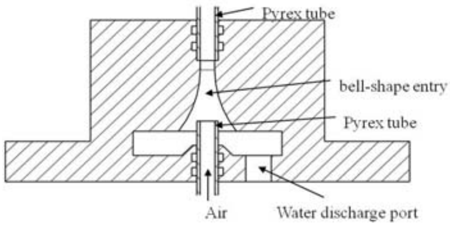


Figure 2: Configuration of the air inlet

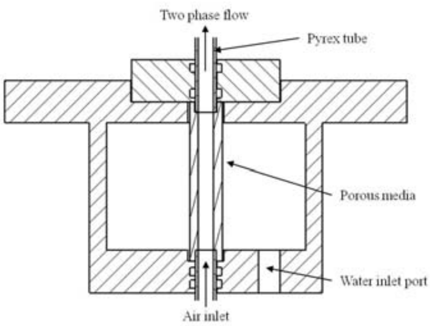


Figure 3: Configuration of the mixer

The test section tube with 7mm i.d. and 1m height was made of Pyrex glass in order to observe flow phenomena. Experiments were performed in this study using various tubes their inclination varied from vertical to horizontal crank type with various horizontal lengths. The configuration of section tubes is shown in Figure 4 and the dimensions are summarized in Table 1.

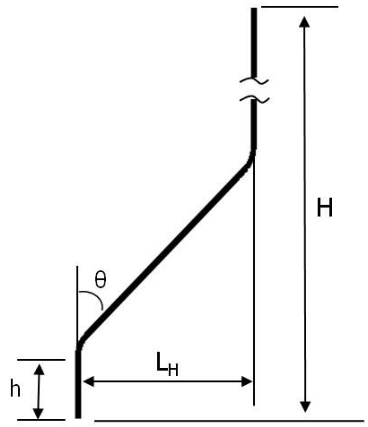


Figure 4: Configuration of test section

Table 1: Test section dimensions

Configuration	vertical	inclined			crank-type			
θ	0°	30°	45°	60°	90°			
L_H (m)	0	0.3			0.3	0.2	0.4	0.5
h (m)	0.1							
H (m)	1							

2.2 Test Procedures

Separate tests with different procedures were performed for CCFL (flooding) and flow reversal study. At each time starts of flooding test the air flow needle valve was closed. Liquid pump was turned on at a set value to supply liquid to fill the mixer tank. The liquid supplied flowed into the tube blow the mixer through porous media section. When the liquid level in the mixer tank was stationary, the desired liquid flow rate was established. The liquid superficial velocity at this test was calculated by the reading of liquid flow meter at that moment. Subsequently the air flow valve was opened and the air flow rate was adjusted to increase progressively until flooding is observed. At this moment the gas critical superficial velocity for flooding was calculated by the reading of gas flow meter.

For flow reversal test, at the start of each time, the air valve was opened firstly and a enough high air flow rate was established. Then liquid pump was opened to supply a certain liquid flow rate until the liquid level in mixer tank is stationary. Subsequently the air flow rate is progressively decreased until flow reversal is observed. Both water and oil are investigated in turn for each section as described above. Two thermal indicators are used to monitor the temperatures of gas and liquid in order to eliminate the temperature influence on fluid density. The densities of gas and liquid are defined by the real-time temperature and atmospheric local pressure.

All experiments are conducted at ambient temperature and pressure conditions. The phenomenon inside test tube is directly observed using a high speed camera at a shutter speed of 1/500 second. Recordings were made at two different locations, below the mixer and above the mixer.

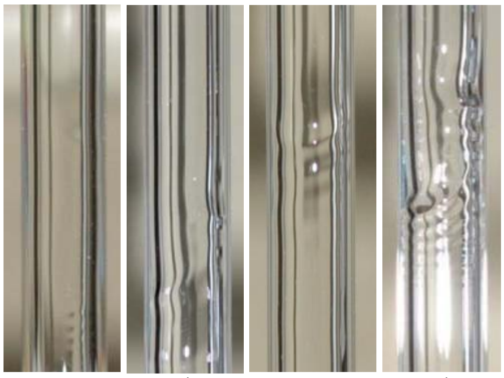
3. Results and Discussion

3.1 Flooding

By observing phenomena of flooding, wave instability plays a dominant role in triggering flooding for both water and oil. At begin, liquid enters the tube through porous media section without air flow. So the liquid introduced flows downward as a stable thin film along whole circumference of tube inside wall (Figure 5, a). If a low air flow rate supplied, the liquid film disturbed by air flow and a few sine waves with small amplitude are generated in the low portion of tube blow mixer (Figure 5, b). As air velocity continues to increase gradually, the waves move upward to higher portion and grow with instabilities (Figure 5, c). Unstable waves collide each other until the waves are converted into large roll waves. And the location of large roll waves move closer to the liquid inlet and become more instable (Figure 5, d). Then, even thought air velocity increases a little. The flow configuration would turns into a chaotic flow pattern and slugging occurred to result in onset of flooding eventually. It can be observed that some of liquid start to flow upward carried by gas and the down flow liquid decreases significantly. At this time, the chaotic flow pattern above mixer chamber expands fast toward to exit of test section tube until liquid spray out. It is speculated that the appearance of large roll waves is a precursor of flooding and the instability of roll waves is the mechanism of triggering flooding.

The flooding data in vertical section (θ=0°, L_H=0m) are shown in Figure 6, where data obtained with water and oil. We performed flooding experiments using Wallis liquid dimensionless velocity rang $0.28< j^{*}_{f}{}^{1/2} < 0.65$ for water and $0.13< j^{*}_{f}{}^{1/2} < 0.38$ for oil because the oil with higher flow rate will block the small diameter tube due to its high viscosity. For both water in the range of $j^{*}_{f}{}^{1/2} > 0.46$ and oil in entire rang, air flow rate needed to cause flooding is inversely proportional to the liquid flow rate (Figure 6) which coincides Wallis correlation well. It is obvious that flooding occurred more easily at high liquid flow rate. That is because as the liquid flow rate is increased the liquid film partially blocking the channel become thicker to results the area available for gas flow reduction especially where large roll waves occur.

The flooding data for water in the range of $j^{*}_{f}{}^{1/2} < 0.46$ seems to indicate that air flow rate triggering flooding is insensitive to liquid flow rate. It can be explained by observed phenomena in Figure 7. In present experiments, if $j^{*}_{f}{}^{1/2} < 0.46$, the water with low flow rate can't wet entire circumference of tube. Even though air flow, water flow downward on inside wall of tube just as a rivulet (Figure 7, a) contrary to a film flow (Figure 7, b) which formed when $j^{*}_{f}{}^{1/2}$ larger than 0.46. The water rivulet film thickness can't be expected to be thinner as water flow rate is decreased due to its non uniformity and uncertain flow path. Therefore the flooding data at low water flow rate can't conform to Wallis correlation in this study. While, there is a fairly good agreement between data and Wallis correlation at low oil flow rate since oil always flows as an entire film because of its lower surface tension.



a b c d

Figure 5: Sequence of phenomena leading to flooding

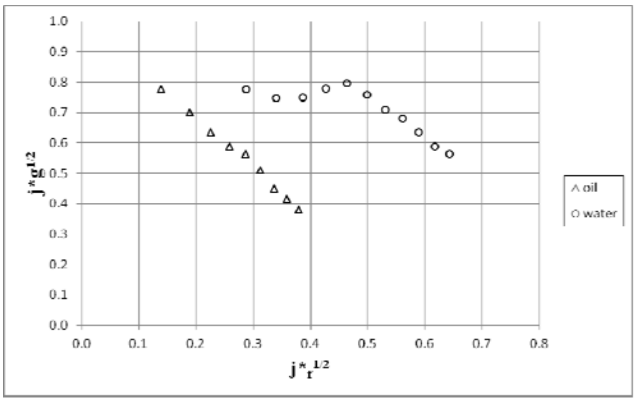


Figure 6: Flooding data for vertical test section

a b

Figure 7: rivulet flow and film flow

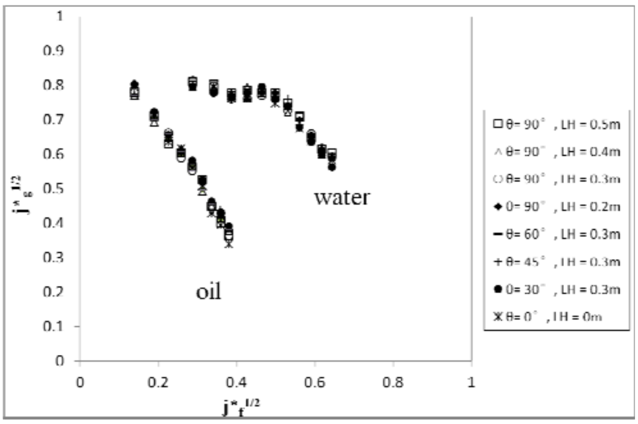


Figure 8: Flooding data for various configurational sections

The flooding data representing for various section configurations are plotted and compared in Figure 8. Both water and oil data are insensitive to the inclined angles and horizontal length of crank-type section tube. Mouza *et al*. (2000) also experimental investigated flooding in a 7mm diameter tube for various inclined angles. However, they reported that the critical gas velocity for onset of flooding tends to increase with decreasing angle of inclination, with respect to vertical. The reason is that the liquid injection was located on top of section in their study, while the location is at the bottom in present work as description in schematics of experimental apparatus (Figure 1). In this case, no water flows in test section above mixer prior to onset of flooding. Therefore, the flooding data would not be influenced by the type of section tube. Furthermore, in view of the data in liquid velocity range overlapped between water and oil, the critical air velocity causing flooding for oil is much smaller than the one for water.

3.2 flow reversal

The flow reversal data representing for various configurational sections are displayed in Figure 9 where obtained water and oil phase data for various liquid flow rates same as water flow range for flooding test. Flow reversal point defined as the air flow rate when the liquid film begins to flow downwards in the tube below the liquid inlet location. Before this time, whole supplied liquid flows upward propelled by sufficient air velocity. Once flow reversal phenomena occurs, as the air flow rate inducing continually more and more water penetrate to flow down from water inlet until liquid film formed.

As shown in Figure 9, regarding each section tube, plotting data represent that the air flow rate at flow reversal point had almost similar values for various liquid flow rates. The effect of liquid flow rate on flow reversal is quite small that is different from flooding phenomena. The flow reversal data for oil are plotted in higher air flow range than those for water. It means that oil is easier to penetrate air flow to flow downward than water when air velocity is inadequate. In other words, oil need higher air velocity than water to keep all of them flowing upward in a certain tube.

The plot also indicates that the shapes of section tube have an effect on flow reversal point. For either water or oil, the critical j^*_g for initiation of flow reversal tends to increase with increasing angle of inclination as well as increasing horizontal length of crank-type section tube. As displayed in Figure 9, the lowest air dimensionless velocity for initiation of flow reversal is obtained in vertical tube (θ=0°, L_H=0m) and the highest one is obtained in the crank-type tube which has the longest horizontal length (θ=90°, L_H=0.5m). Same tendency for flow reversal in crank-type tube with different horizontal lengths also be confirmed by Lee *et al*. (2004). They tested the length effect on flow reversal using a test section with 10.7mm i.d. However, the effect by angles of inclination was not investigated in their study.

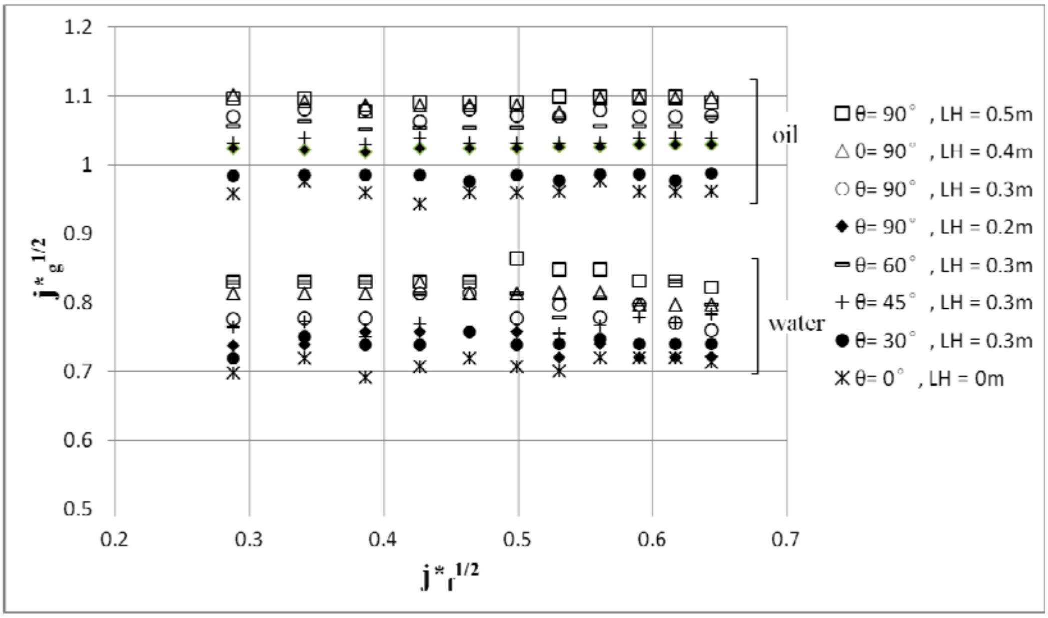


Figure 9: Flow reversal data for various configurational sections.

3.3 Criteria for oil return

The liquid flow rates at flow reversal point equals to zero. Conform to Equation (4), C represents the critical dimensionless gas velocity for zero penetration of liquid. Thus the refrigerant load (mass flow rate) in real refrigerator can be predicted by equation (5) if the constant C is obtained. According the flow reversal data in Figure 9, the range of constant *C* is from 0.96 to 1.09 depending on different shapes of tube. In view of the cabinet width and more complexity of suction pipe in real refrigerator, the maximum gas velocity *C = 1.09*, for the tube configuration θ=90°, L_H=0.5m, is recommend for security of oil return. Consequently, according to equation (5), the criterion predicted can be expressed as following:

$$j_g = 1.2\square\left(\frac{g d_i(\rho_f - \rho_g)}{\rho_g}\right)^{1/2}$$

3. CONCLUSIONS

Flooding and flow reversal characteristics of counter-current gas-liquid two phase flow were experimentally investigated. Transparent 7mm inner diameter Pyrex-glass tubes with 1m height were used as test sections. Experiments were performed with vertical, inclined (with inclination angle from 30° to 90°) and crank-type (with horizontal length from 0.2m to 0.5m) configurations of section tubes, using air as the gas phase and water and oil as the liquid phase.

In present work, the location of liquid injection was placed at the bottom of test section. The flooding data were insensitive to different configurations of test section, but greatly affected by liquid flow rates. The critical air velocities for onset of CCFL are inversely proportional to the liquid flow rate. CCFL data were correlated using Wallis dimensionless velocity j^*_f for liquid and j^*_g for air respectively. For water and oil, the plot showed that Wallis correlations had a good agreement with experimental data but in low water flow range ($0.28 < j^{*\,1/2}_f < 0.46$) where Wallis correlations did poor prediction since water film couldn't wet entire circumference of tube. By observing phenomena, it was obvious that the growth and propagation of large roll waves which generated on surface of liquid film were main mechanism for initiation of flooding.

The minimal air velocities leading flow reversal for various liquid flow rates were quite similar. Comparing with water, the results suggested that oil need higher gas velocity to avoid from flow reversal in section tube. Furthermore, for configurations of section tube, both angle of inclination and horizontal length of crank-type were effective factor for flow reversal happening. Higher air velocity was needed if the angle was increased as well as horizontal length. It is important for oil return design. The value of Wallis parameter, *C* = 1.09 was empirically suggested.

NOMENCLATURE

d	diameter	(m)
g	gravitational acceleration	(m/s^2)
j*	Wallis parameter	(-)
V	velocity	(m/s)
α	fraction	(-)
ρ	density	(kg/m^3)

Subscripts

f	liquid phase
g	gas phase

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